INTEGRATING THE FLEXIBILITY OF THE AVERAGE SERBIAN CONSUMER AS A VIRTUAL STORAGE OPTION INTO THE PLANNING OF ENERGY SYSTEMS

by

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With the integration of more variable renewable energy, the need for storage is growing. Rather than utility scale storage, smart grid technology (not restricted, but mainly involving bidirectional communication between the supply and demand side and dynamic pricing) enables flexible consumption to be a virtual storage alternative for moderation of the production of variable renewable energy sources on the micro grid level. A study, motivated with energy loss allocation, electric demand and the legal framework that is characteristic for the average Serbian household, was performed using the HOMER software tool. The decision to shift or build deferrable load rather than sell on site generated energy from variable renewable energy sources to the grid was based on the consumer's net present cost minimization. Based on decreasing the grid sales hours of the micro grid system to the transmission grid from 3,498 to 2,009, it was shown that the demand response could be included in long-term planning of the virtual storage option. Demand responsive actions that could be interpreted as storage investment costs were quantified to 12 €peryear in this article.

Key words: *electric hot water thermal storage, smart grid, HOMER software, variable renewable energy*

Introduction

On the pathways to sustainable energy systems, the integration of variable renewable energy sources (V-RES) has always been followed with moderation from various storage options [1]. Utility scale V-RES moderation (*e. g.*, pumped hydro storage plants) increases energy loss, while line distances and loss in conversion are significant. Electric current allocated losses in distribution transformers and lines could be more than 10% of the total generation [2]. The challenge of integrating more V-RES electricity production has to be co-ordinated with other types of storage, *e.g.*, heat storage [3, 4]. Energy transmission over distance lines is not a favourable option for small scale wind and solar photovoltaic (PV) systems due to transformation losses. When electricity is transported and distributed thought the grid losses occurred in the case of unmatched production and consumption (grid sales or grid purchases). As it is generated near the end-user, V-RES energy does not have to be transmitted across transmission and distribution lines. Moreover, it does not need to undergo any transformation (step-up or step-down) to serve a distant load. This means that all of the costs of typical line

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losses associated with remote, centralized generation resources and transmission and distribution to the end-user are saved and should be quantified [5]. In Serbia, technical losses in distribution are estimated to be 8.6% [6]. A load flow study on 33 node network [7] showed that technical losses in distribution could be decreased from 7% to 5.87% of fixed consumption with the proper placement of grid-connected, roof-mounted solar PV system. A further decrease is possible with better matching of the micro grid production and the consumption and minimization of the energy flows.

Real time pricing – an economic precondition for integration

Real-time pricing (RTP) rates vary continuously over time in a way that directly reflects the wholesale price of electricity, rather than at pre-set prices as in Time-of-use (TOU) tariff rate designs [8]. The Energy Community is extending the European Union's internal energy market to Southeast Europe and, on the ground of a legally binding treaty, implementing the relevant EU regulations concerning the energy sector step-by-step [9]. Small consumers in Serbia are currently supplied on a TOU tariff. The switch to RTP, reflecting the regional electricity wholesale market price, as an expected next step after historical and marginal costs pricing [10] has been scheduled for 2015. It could occur even sooner with granting guarantee access for new supply market entrants under a transparent regulatory regime from mid 2014 according to the last draft amendments to the Energy Law [11]. This has been an obligation of third internal market package implementation since March 2011 [9]. Economic valuing of demand responsive actions to the RTP has been new paradigm [12] since 2006. One can show that consuming V-RES locally is economically preferable and the total operating cost difference over one year is the value of the storage option that could be invested in equipment that increases customer flexibility (smart grid equipment). This investment would reduce buying electricity from the grid and in the long-term payback itself based on better utilization of V-RES investment. The savings emerging from flexibilization of the consumption on a monthly level could be achieved [13] at 5-10 $ month according to a stydy [8]. Real-time pricing (to some degree time-of-use pricing) is derived from the economics-based model, conveying a price signal to motivate a customer demand response that would modify their usage patterns and to realize financial gains and losses from their actions or inactions [14]. The flexible energy consumption to break-even in the spot market will decrease significantly, as low as 1 kWh [15], opening the market for demand responsive consumers, which could result in a revenue of 9-13 €/(year kWh) as in the case of Denmark.

For a decision on the best demand response resource to be used as virtual storage in Serbia, the most important consumption characteristics of an average household were accessed. The characteristics were a high share of electricity consumption for hot water thermal storage heating of 4.8 TWh per year and a high availability of electric hot water thermal storage of 89% in the households [16]. This is a high share in end-user energy (34%) [17] compared to the EU and USA (less than 10%) [13].

Smart grid – a technical precondition for integration

The virtual storage based on smart grid (SG) solution and emerging from demand response is an alternative to utility scale storage that could contribute integration of V-RES [18, 19]. Moreover, a smart grid enables bidirectional communication between the supply and demand side, which is also a technical precondition for a RTP. A micro grid, as a part of a SG, with a demand side management (DSM) function of building and deferring demand, can help balancing consumer's loads with generation locally minimizing the energy flows. When properly planned as part of the overall grid design, such a micro grid could result in better average capacity factors [20] and better utilization of equipment and investments.

Deferrable load is a manageable electrical load that must be met within a certain time period, but the exact timing is not important. Loads are classified as deferrable because they have some storage associated with them [21]. The ability to defer serving a load is often advantageous for systems comprising intermittent renewable power sources, because it reduces the need for precise control of the timing of power production. If the renewable power supply ever exceeds the primary load, the surplus can serve the deferrable load rather than going to waste (excess electricity production) [4, 21] or to be sold to a grid with an unfavourable price. The virtual thermal storage approach has been part of the tariff in Serbia with the option to switch off and on electric space heating devices from the grid according to presence of other loads in the system, with the aim to reduce the peak load of the system [22]. This was not popular due to the obligations of fixed load reduction in advance that could not be altered, which customers may find not enough usable. The more usable load building and deferring of, *e. g.*, an electric hot water thermal storage heater should be based on consumer occupancy schedules, time-of-use schedules and on critical peak events [23]. A demand responsive electric hot water thermal storage load then becomes a virtual storage option for the moderation of V-RES that reduces excess electricity production [4] and grid sales.

Demand response as part of a planning methodology

Demand response program designs have evolved since they were first introduced in the late 1800s, but the management of customers cost was possible only after the year 2000 with a SG [14]. Two fundamentally different approaches in the development of all demand response planning options are relied on: changes in customer electricity use and on a technology infrastructure to affect the changes in customer electricity usage without overt involvement of the customers [14]. Demand response options were evaluated as alternatives to generation and transmission/distribution resources in the first demand response planning methodology developed in 1980s [14]. The demand response planning approach is the reverse of a classical supply planning process, generally beginning with the assumption that both the end-use characteristics (demand side) and cost from the resource plan (supply side) would remain unchanged [14]. The systematic planning process requires tracking of the system load duration curve to and end-use load curves [14, 24]. The value of the demand response is driven by its ability to defer, curtail, or build demand at a lower cost than the conventional generation resources already in the resource plan [14] This was motivated by the fact that, usually, investment costs per MW of consumer equipment are an order of magnitude lower than the generation eqipment [25]. Planning models traditionally used to optimize investments in generation, have recently been extended to integrate short term demand response not only through reducing energy use, but also by facilitating the integration of renewable energy [26]. Demand responsive actions could be included in the long-term planning virtual storage option based on the duration curves of grid sales.

In a simulation of a small scale wind and PV micro grid system in Belgrade, it was shown that by adding electricity storage, a better matching of the production and consumption of electricity over the whole year could be achieved [27]. The mismatch between production and demand from a single family house for electric hot water thermal storage was studied by conducting a thermal simulation in TRNSYS, which showed that the recharging strategy was more effective both technically and economically than an electrical battery [28]. This study also showed that the sensitivity of the annual mismatch (value that is proportional to the grid sales) to a further increase in storage size (above the daily consumption of hot water) was not significant and could even be negative. Another study [13], based on heat transfer model of electric hot water thermal storage (150-300 L), with different u-values and control algorithms, showed that end-use consumption of renewable energy (wind) was increased. A study using EnegyPLAN [29] showed a significant contribution of demand response as a moderation strategy to reduce energy imbalances and to an increase of wind power penetration into a national energy system. HOMER has been used mainly for planning renewable micro grids [30, 31] and their optimal sizing [7, 32-38] based on the minimal levelized costs of energy (COE) and net present costs (NPC) criteria under different constraints. Its suitability for Serbia was proven by a comparison of measurement data [39]. In HOMER, it is possible to treat deferrable load inputs like storage in water pumping, ice making and battery charging examples. A different approach to simulate flexible consumption of electric hot water thermal storage was used in the present study, which is explained in the Method chapter.

Our planning method is based on duration curves of grid sales obtained by hourly simulation of the historical yearly fluctuations in production, consumption and electricity prices.

Methodology

HOMER has been used for a micro power system modelling [21] and for analyzing the integration of renewable energy into an energy system [40]. HOMER is a computer model developed by the US National Renewable Energy Laboratory (NREL) to assist in the design of micro power systems and to facilitate the comparison of power generation technologies across a wide range of applications. HOMER models a power system physical behaviour and its life-cycle cost, which is the total cost of installing and operating the system over its life span. HOMER allows the modeller to compare many different design options based on their technical and economic merits. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs [21].

An introduction to the HOMER model

HOMER performs three principal tasks: simulation, optimization, and sensitivity analysis, (fig. 1).

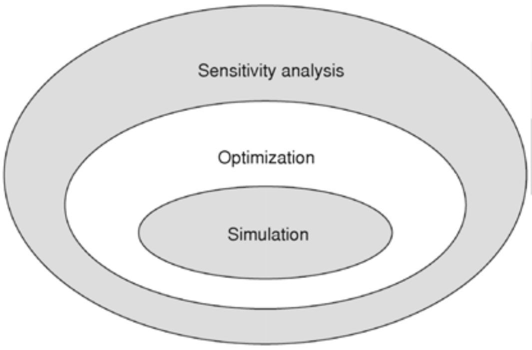
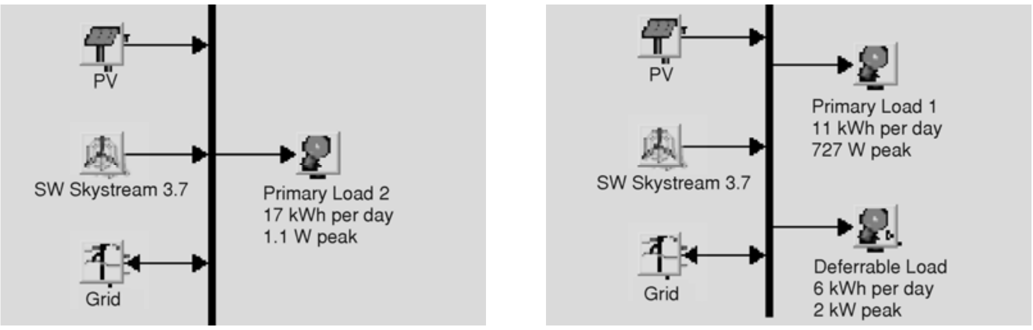


Figure 1. Conceptual relationship between simulation, optimization, and sensitivity analysis [21]

Scenarios: Serbian average household hourly load simulations

Serbia must increase its RES production, according to the National Renewable Action Plan, by 1.25 TWh [41] by 2020. Its RES technical potential for decentralized generation is much greater [42] *e. g.* in solar thermal collectors to generate heating energy is about 1.75 TWh annually if one in five (1/5) households installs 4 m^2 [43]. Configuration diagrams for two scenarios with different scales of load flexibility, reference and consumer flexibility scenarios are shown in fig. 2.



(a) **(b)**

Figure 2. Scenarios: (a) reference and (b) consumer flexibility

Reference scenario.

The historical load curve for Serbia [44] was scaled assuming the same hourly pattern and load factor to one household, *i. e.*, an AC primary load of 6,030 kWh per year with peak load scaled to 1.1 kW.

Consumer flexibility scenario

This scenario has the same yearly load as the reference scenario but with a different scale of flexibility. The load was divided into a primary load of 3,840 kWh per year (that is not deferrable) and deferrable load of 2,190 kWh per year.

The deferrable load was used to model consumer flexibility during one day. The deferrable load was modelled as electric hot water thermal storage with load of 2 kW and storage of 6 kWh per day. A daily consumption pattern for hot water thermal storage was assumed. Using the deferrable load to consume excess V-RES production rather than to sell it to the grid was simulated on an hourly base.

Physical modelling with HOMER

Components

The components used in the modelling process were PV array, wind turbine and the grid. Using HOMER, a high V-RES penetration of 68% was simulated in an energy efficient household, with average electricity consumption (6,030 kWh per year) under two different scenarios of consumer load flexibility. The grid was modelled as a dispatchable source with RTP using historical data of European energy exchange (EEX) from the German-Austrian border. The data were scaled to comply with an average offer to sell a kWh to the consumer at a rate of 10 c€ and to buy it from the consumer at a rate of 8 c€. This price difference was set to motivate local consumption by deferrable load rather than selling to the grid with the associated losses in transmission and distribution. The grid sale and purchase rate difference (transport costs) was set with to the aim of minimize grid sales and minimize energy transport loss. Carefully choosing the sale and purchase rate to be lower and higher, respectively, than on site specific V-RES generation costs economically forces local consumption. The V-RES generation system consisted of a solar PV array system with inverter and an AC small wind turbine. It was also assumed that the PV system of 2 kW peak power was fixed to the south with at a 32-degree slope (without tracking).

Modelling flexible consumption in HOMER (deferrable load inputs)

The resulting average household consumption for electric hot water thermal storage was 6 kWh/(storage·day). The baseline data was a set of 12 values representing the average deferrable load in one household, in kWh. Storage capacity, the size of the storage tank, expressed in kWh of energy needed to fill the tank was set at 6 kWh per day. Peak load, the maximum amount of power, in kW, that could serve the deferrable load in a hot water thermal storage application, was equal to its rated electrical power, assumed to be 2 kW. The minimum amount of power that could serve the deferrable load, expressed as a percentage of the peak load, minimum load ratio was rated as 0%, while the heater could be easily turned off. In the HOMER simulation, the deferrable load would be served whenever a V-RES is generating more electricity than required to serve the primary load. When the level of the electric hot water thermal storage (virtual storage) drops to zero, the peak deferrable load is treated as primary load. The grid would be used as a dispatchable power source and would then serve as much as possible for the peak deferrable load, avoiding that the deferrable load goes unmet [21].

Resources

The solar resource was modelled with historically averaged hourly data of the irradiation at the surface, with average hour of 3.47 kWh/m^2 per day, obtained from NASA. Wind resource seasonal availability was presented with historical hourly measured data with an average speed of 3.61 m/s at 10 m, scaled for the turbine height with a logarithmic wind shear profile and surface roughness length of 0.25 m [45].

Economic modelling in HOMER

Economics play an integral role in both HOMER's simulation process, wherein it operates the system so as to minimize the total *NPC*, and in its optimization process, wherein it searches for the system configuration with the lowest total *NPC* [21]. The total *NPC* condenses all the costs and revenues that occur within the project lifetime into one lump sum in today's dollars, with future cash flows discounted back to the present using the discount rate [21]. HOMER calculates the total *NPC* using eq. (1):

$$C_{NPC} = \frac{C_{\text{ann,tot}}}{C(i, R_{\text{proj}})} \tag{1}$$

where $C_{\text{ann,tot}}$ is the total annualized cost, i – the annual real interest rate (the discount rate), R_{proj} – the project lifetime, and *CRF* (x) – the capital recovery factor, which is given by eq. (2):

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{2}$$

where i is the annual real interest rate and N – the number of project lifetime years. The *NPC* includes the costs of initial construction, component replacements, maintenance, fuel, plus the cost of buying power from the grid and miscellaneous costs, such as penalties resulting from pollutant emissions. Revenues include the income from selling power to the grid, plus any salvage value that occurs at the end of the project lifetime. To calculate the salvage value of each component at the end of the project lifetime, HOMER uses eq. (3):

$$S = C_{\mathrm{rep}} = \frac{R_{\mathrm{rem}}}{R_{\mathrm{comp}}} \tag{3}$$

where S is the salvage value, C_{rep} – the replacement cost of the component, R_{rem} – the remaining life of the component, and R_{comp} the lifetime of the component. The total operation and maintenance (O&M) cost of the system is the sum of the O&M costs of each system component. The grid O&M cost is equal to the annual cost of buying electricity from the grid (energy cost plus a fixed demand cost) minus any income from the sale of electricity to the grid. HOMER calculates the levelized *COE* using eq. (4):

$$COE = \frac{C_{\mathrm{ann,tot}}}{E_{\mathrm{prim}} + E_{\mathrm{def}} + E_{\mathrm{grid,sales}}} \tag{4}$$

where $C_{\mathrm{ann,tot}}$ is the total annualized cost, E_{prim} and E_{def} are the total amounts of primary and deferrable load, respectively, that the system serves per year, and $E_{\mathrm{grid,sales}}$ is the amount of energy sold to the grid per year. In its optimization process, for example, HOMER ranks the system configurations according to NPC rather than the levelized *COE*. Economic benefit for the consumer is obtained from the fact that local generation could be economically preferable than buying from the grid. The capital costs of the PV system (PV panels, mounting hardware, control system, wiring and installation) was assumed to be 740 €/kW) with a de-rating factor of 80% in a lifetime of 15 years, after which it has to be replaced at cost of 400 €/kW. For a small wind turbine of 1.8 kW (SW Skystream 3.7) with a hub height of 33.5 m, the investment cost was assumed to be 3,000 € with O&M costs of 30 € per year and a 20-year lifetime. The real annual interest rate over the 25-year planning period is 10%.

Electric hot water thermal storage peak load and size sensitivity analysis

The storage size has an influence on the availability to match production and consumption of a household avoiding energy sales to the grid. With a higher peak flexible load, a higher V-RES size could be matched. If the flexible load size is greater, the V-RES load could be moderated over a longer period, but significant over dimensioning does not have positive effects [28]. Therefore two sensitivity analysis to the grid sales in the presence of V-RES generation have been presented: a decrease in the peak load and a decrease in the deferrable load size. Sensitivity analysis of peak deferrable load [kW] for decreased sizes (to 50%, 25%, and 0%) keeping the storage size fixed at 6 kWh/d was realised. Additionally, deferrable load size decreases (to 75%, 50%, 25%, and 0%) sensitivity analysis was performed, keeping the peak deferrable load fixed at 2 kW.

Results

Production and consumption of a micro grid (an average Serbian household with V-RES and the grid) is shown in fig. 3. The data resulted from hourly simulations of both scenarios for the whole year and from modelling assumptions, *e.g.*, to include grid sales as useful energy consumption [21].

The total yearly consumtion in the flexibility scenario (primary and deferrable load) is the same as the yearly consumption in the reference scenarios (primary load). Consumption is equal to the production in both scenarios. The production and consumtion are lower in flexibility scenario because grid sales and purchases are lower.

The hourly production and consumption for one day are shown in fig. 4 and referred to the left axis. It could be observed that in consumer flexibility scenario (dotted line with "♦")

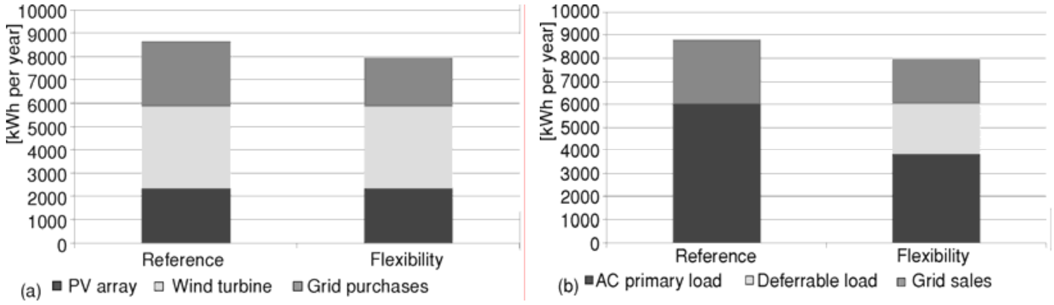


Figure 3. (a) Micro grid yearly production and (b) consumption

in the presence of deferrable load (firm line with "—"), the production and consumption were better matched and grid sales were postponed, compared to the reference scenario (firm line with "●"). Grid sales (dotted line with "×") that occurred in the reference scenario due to V-RES generation (PV: firm line with "■", wind: firm line with "▲") were shifted in the consumer flexibility scenario with a deferrable load to 12 a. m. (firm line with "-") because the deferrable load then matches the V-RES generation better. Daily sellback rate development is show by the dotted line with "+", referring to the right axis.

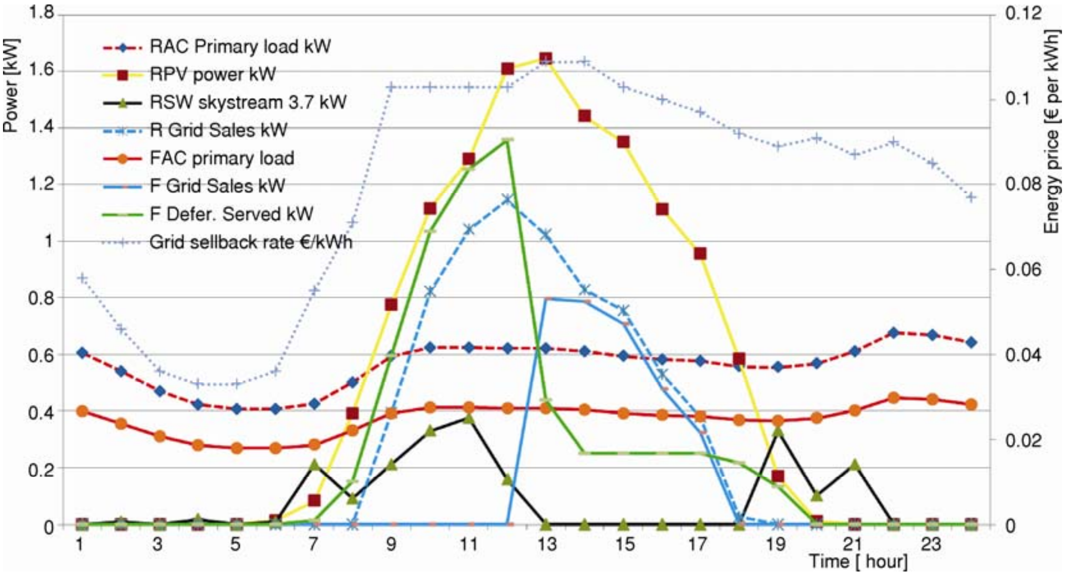


Figure 4. With deferrable load (F Defer Served kW) better matching between production and consumption was achieved. Grid sales (F Grid Sales kW) were postponed by four hours, compared to the reference case (R Grid Sales kW) (Date: May 6th) (for color image see journal web site)

The storage peak deferrable load [kW] and size [kWh] have an influence on the possibility of matching production and consumption of a household and thereby avoiding grid sales. The sensitivity analysis of the peak deferrable load to the grid sales is shown in fig. 5 as load duration curves.

Figure 5 shows that grid sales were increased with decreasing peak flexible load. In the base case of 2 kW of peak flexible load, the duration of grid sales was 2,009 hours annually. This increased to 2,256 and 2,827 hours annually in the case of peak deferrable load decreases to 1 kW and 0.5 kW, respectively, and to 3,498 for the case of zero (0) peak deferrable load.

The sensitivity analysis of deferrable load size (kWh) to the grid sales is shown in fig. 6 by its load duration curves for the base case of 6 kWh per day and four (4) cases of decreased load size.

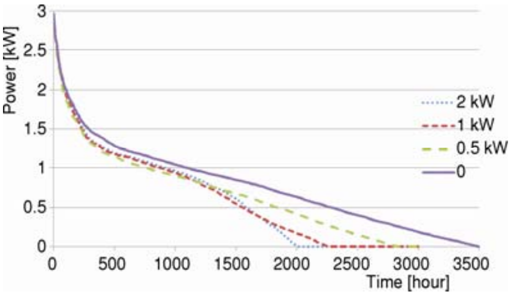


Figure 5. Sensitivity analysis of power sold to grid duration curve to peak deferrable load
(for color image see journal web site)

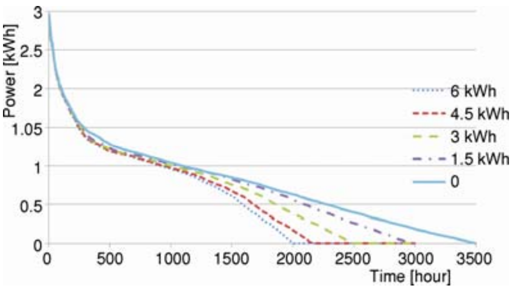


Figure 6. Sensitivity analysis of power sold to grid duration curve to deferrable load size
(for color image see journal web site)

The grid sales increased with decreasing flexible load storage. From around 2,000 hours annually in the reference case, the grid sales increased to 2,158, 2,492, 2,964 and 3,498 hours annually when the flexible load decreased to 4.5 kWh, 3 kWh, 1.35 kWh and 0 kWh, respectively.

Table 1 gives an economic comparison of the two scenarios.

Table 1. Economic comparison of the reference (R) and consumer flexibility (F) scenarios

	Total capital cost	Total NPC	Total O&M cost	Grid O&M cost	COE	Grid purchases	Grid sales	Grid net purchases	Ren. fraction
	€	€	€/year	€/year	€/kWh	kWh/year	kWh/year	kWh/year	
R	4,480	5,853	107	47	0.107	2,780	2,632	148	0.68
F	4,480	5,746	95	35	0.105	2,051	1,908	143	0.74

Total capital costs were the same in both scenarios, while the same equipment was purchased (no additional equipment was purchased for the consumer flexibility scenario). The total NPC of the system over the planning horizon in the consumer flexibility scenario was decreased by 107 €. The total O&M costs in the case of customer flexibility were lower because of fewer grid purchases. The levelized COE were decreased from 0.107 €/kWh in the reference scenario to 0.105 €/kWh in the consumer flexibility scenario. The total yearly savings in operational costs for the consumer were 12 €. These savings arise from the fact that the consumer achieves better utilization of the investment in the V-RES equipment in the consumer flexibility scenario. The flexible electric hot water heater functioned as a thermal storage that was used for market price arbitrage. Forced energy export to the grid (grid sales) were then decreased or postponed to times when the price was better. Energy transmission and distribution was minimized in the consumer flexibility scenario and therefore grid purchases were reduced to 77%, while grid sales were reduced to 72%, in comparison to the reference scenario. Better matching of household consumption with V-RES production resulted in fewer net grid purchases in an increased share of RES in the total electricity consumption of a household from 68% to 74%.

Conclusions

With flexible electric hot water thermal storage during one day, the grid sales were decreased, consumption was better matched with on site production of variable renewable energy sources and, therefore, energy loss due to two -way energy transmission and distribution could be decreased.

The renewable fraction in total electricity consumption was increased due to a better matching of household consumption with V-RES production in the flexible consumption scenario.

Levelized costs of energy and the total net present and yearly energy costs for the consumer were decreased with flexible consumption.

Based on simulations in HOMER, decreasing excess grid sales, increasing the renewable fraction in the total electricity consumption and decreasing energy costs as result of flexible electric hot water thermal storage, a variable renewable energy planning methodology could be obtained for a single household. Extension of this planning methodology is possible for the case of planning the national energy system.

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